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12

SURFACE MELTING OF ROTATING BANDS

NOVEMBER 1975

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

TECHNICAL REPORT

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The point at which a complete molten film is formed on the surface of projectile rotating bands is very important because, when it is formed, sliding becomes lubricated and friction determined by hydrodynamic considerations alone. Furthermore, beyond this point, wear of a particular band material is dependent only on the amount of heat transferred to it. The first formation of the molten surface film for projectiles with gilding metal bands was estimated by observing the location of the drop in the

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coefficient of friction. This was reached well before the bands were completely engraved in the case of a 155mm howitzer firing at low zones. It would be reached even more rapidly in the case of tank guns or artillery firing at higher zones.

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(10) ROBERT S. MONTGOMERY

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TABLE OF CONTENTS

	Page
Experimental Determination of Rotating Band Surface Melting in a Gun Tube	2
Calculation of Coefficients of Friction During the Engraving Process	4
Results	9
Conclusion	9
References	10
Acknowledgment	10

TABLES

TABLE I 155mm M185 Howitzer Firing Data (1.0 in to 20.0 in.)	11
TABLE II 155mm M185 Howitzer Firing Data with M107 Projectiles and Tube No. 2. (.14 in to .32 in)	14

FIGURES

Figure 1 Cross Section of the Rotating Band on the 155mm M107 Projectile	6
Figure 2 Coefficient of Friction as a Function of the Product of Bearing Pressure and Sliding Velocity for Gilding Metal Rotating Bands	8
Figure 3 Penetration as a Function of Pressure for Gilding Metal of 40 R_B Hardness (Derived from Data in Reference (2)).	16
Appendix-Calculation of Coefficients of Friction During the Engraving Process	15

Surface Melting of Rotating Bands

The point at which a complete molten film is formed on the surface of projectile rotating bands is important to the muzzle wear problem as well as to the "low-zone sticker" problem, origin-of-rifling erosion, etc. When the molten surface film is formed, sliding becomes lubricated and friction determined by hydrodynamic considerations alone. Furthermore, after an adequately thick film has been formed, wear of a particular band material is dependent only on the amount of heat transferred to it.

A complete molten surface film was formed in laboratory high-speed pin-on-disk experiments at a pressure-velocity value of approximately 3×10^6 (psi)(fps) with gilding metal, annealed iron, pure copper, and projectile steel.[1] The formation of the molten surface film with the latter two materials was indicated by an abrupt drop in friction coefficients from high and unstable values and a similar abrupt drop in wear rate. These results based on laboratory data, however, cannot be extended to an actual projectile in a gun tube without taking into account some additional factors which influence the formation of the surface film.

During the initial travel of a projectile, the rotating band is forced into the rifling or "engraved". This results in severe working of the band material which was not present in the laboratory experiments. The heat generated in this way during the engraving process is a significant fraction of the total although it is not confined to the sliding interface. In addition to this, heat is transferred from the

[1] R.S. Montgomery, "Friction and Wear at High Sliding Speeds", Watervliet Arsenal Report 75028 (1975).

hot propellent gases during engraving. The rear three-quarters or more of the rotating band is completely surrounded by these gases at the start of motion. Furthermore, the gun tube surface near the origin-of-rifling is ordinarily hot owing to previous firing. All the above factors cause the molten surface film to be formed more rapidly on actual rotating bands than predicted from the laboratory experiments. There were also other differences between the laboratory experiments and the actual situation in a gun tube. The laboratory experiments were made at constant velocity and bearing pressure while both of these change continually in a gun tube. Furthermore, the laboratory experiments were made at lower bearing pressures than actually experienced in a gun tube. For example, the mean band pressure during the initial travel of a projectile with gilding metal rotating bands is in the range of 50,000 psi while the bearing pressures for the laboratory gilding metal experiments did not exceed 14,000 psi although they were as high as 20,000 psi with some of the other materials. It is not known how these differences influence the formation of the molten surface film.

<u>Experimental Determination of Rotating Band Surface Melting in a Gun Tube</u>

The point at which a molten surface film first forms can be estimated by observing the location of the drop in the coefficient of friction. Accurate measurements have recently been made by the Feltman Research Laboratory at Picatinny Arsenal for the first few inches of travel on rounds fired at low zones in a 155mm M185 howitzer tube. The pressure of the propellent gases was measured at the breech and the acceleration of the projectile measured by means of a strain gage type accelerometer mounted in the fuze cavity of the projectile and the signal transmitted through a wire lead out of the muzzle of the cannon. Since only low zones were used, accelerations were moderate and the system worked well. The projectile location and velocity were calculated from the acceleration values and the thrust on the projectile calculated by multiplying the propellent gas pressure by the area of the base of the projectile. The resistance (Rforce) at any location could be calculated as the difference between the thrust and the force required to produce the observed acceleration.

In order to convert these resistance forces into coefficients of friction, the normal force on the wall of the tube must be known. After engraving, for the next few inches of travel this can be taken as the product of the bearing area of the rotating band and the mean wall pressure as determined from slow-speed push tests. In this region, the centrifugal load of the projectile on the tube wall is low and there has not yet been significant wear on the bands. The mean band pressure was determined for the 155mm M118 illuminating projectile and the 155mm XM549 projectile as 50,000 psi by means of circumferentially mounted strain gages on the tube near the origin-of-rifling in the former case and by means of strain gages on the projectile as well in the latter case.(2) The M118 projectile has the same gilding metal rotating bands as does the M107 projectile and push tests on M107 and M483 A1 projectiles indicate that this value can be used for them as

[2]W. F.Hartman and P. P. Stirbis,"Rotating Band Pressures and Engraving Forces in 155mm Gun Tubes as Deduced from Quasi- Static Push Tests", U.S. Army Report SC-RR-71 0457 (1971)

well.[3] From the laboratory data on gilding metal, a drop in the coefficient of friction to approximately 0.3 indicates the first development of a molten surface film. The coeffients of friction for a location where the bands have just been completely engraved, calculated using a mean band pressure of 50,000 psi, range from 0.04 to 0.14. Therefore, it can be concluded that the molten surface film is rapidly formed and is, indeed, fully formed by the time the rotating bands have been completely engraved. These experimental firing data are given in Table I.

Calculation of Coefficients of Friction During the Engraving Process

Calculation of the normal force on the gun tube wall during the engraving process is difficult but can be done with a knowledge of the dimensions of the rotating bands and the cannon tube in the vicinity of the origin-of-rifling and of the penetration-pressure curve of the rotating band material. Since the dimensions of the test cannon tubes were not measured, only the data obtained with the most lightly worn tube, tube no. 2, were used and the origin-of-rifling was assumed to be identical with that of a new tube. Only approximately 150 rounds had been fired through this tube so this assumption may not be too much in error. The origin-of-rifling erosion which was present would result in calculated coefficients of friction lower than the actual values but would not change the location of the friction drop which indicates the formation of the molten surface film. The pressure-penetration curve for gilding metal similar to that used in the bands of the M107 projectile was experimentally determined in ref. (2) but

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[2] W.F. Hartman and P.P. Stirbis, "Rotating Band Pressures and Engraving Forces in 155mm Gun Tubes as Deduced from Quasi-Static Push Tests", U.S. Army Report SC-RR-71 0457 (1971)

[3] J.O. Pilcher, U.S. Army Ballistics Research Laboratory, Private Communication (1975)

unfortunately was not available for the softer bands on the M483 A1 projectiles. Therefore, coefficient of friction values could not be calculated for these projectiles prior to complete engraving and only the M107 data were used.

The length of contact of the rotating band with the tube wall was divided into segments. At a location where the rotating band is completely engraved, the coefficient of friction is given by the expression

$$\text{Rforce} = Ff \qquad (1)$$

where, F = normal force on the wall of the tube and

f = coefficient of friction.

Prior to this point, the axial force resulting from the fact that the band is being constricted by the forcing cone must be taken into consideration and the coefficient of friction is given by the expression

$$\text{Rforce} = F(\sin\alpha + f\cos\alpha) \qquad (2)$$

where, α = the wall angle at the forcing cone. In the case of the M185 tube, $\sin\alpha$ is 0.1011 and $\cos\alpha$ is 0.9949. The normal force on the tube wall for each segment was obtained by calculating the penetration (interference). Where there was rifling, the penetrations of the lands and grooves were calculated separately. They were then converted into pressures using the penetration-pressure curve. Actually, the deformations of the gun tube and projectile resulting from the band and propellent gas pressures should be taken into consideration for a rigorous calculation of penetration. However, these components only amounted to

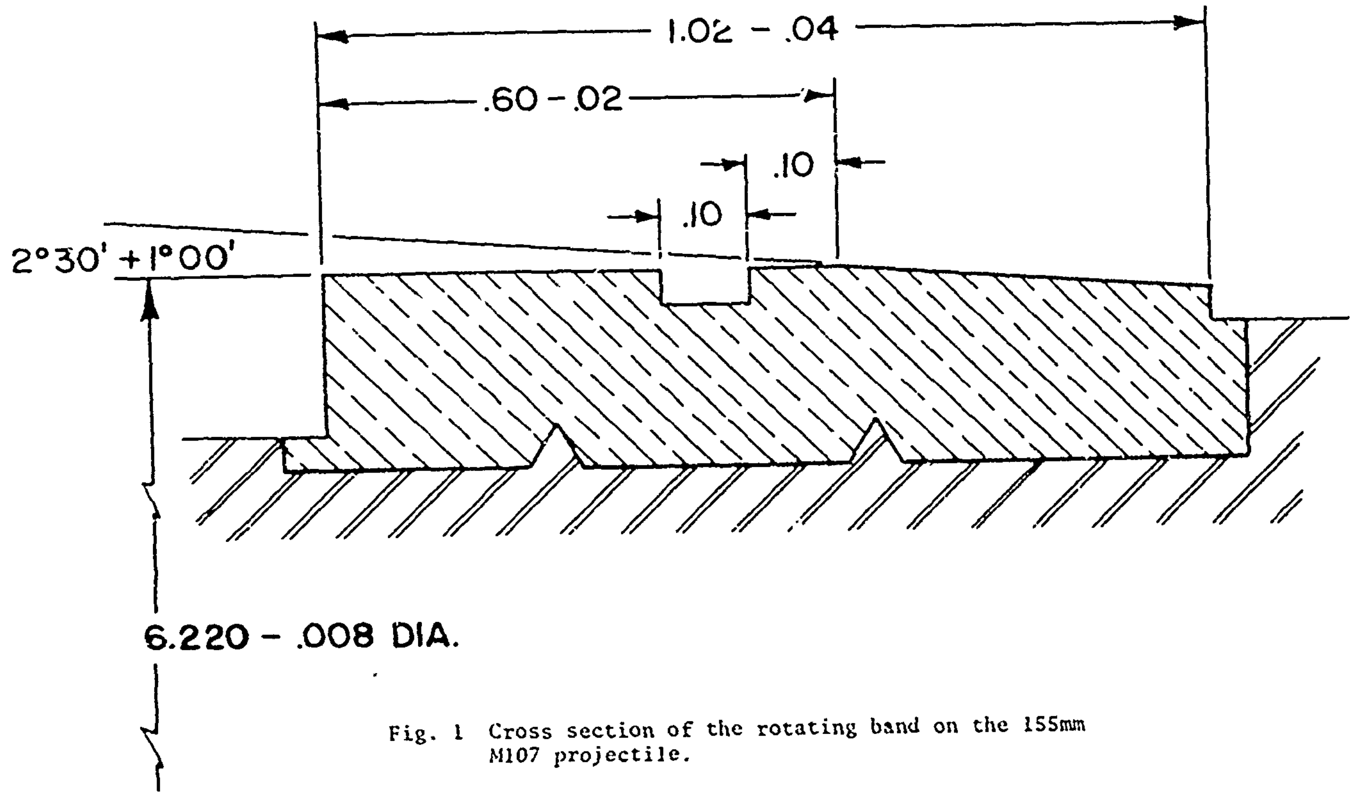


Fig. 1 Cross section of the rotating band on the 155mm M107 projectile.

12% of the total for an M118 projectile engraved in a 155mm M2 howitzer tube (2) and so they could be neglected for these approximate calculations. The pressure for each segment was then multiplied by its respective bearing area to yield the normal wall force. These values, together with the experimental resistance force, allowed the calculation of the coefficients of friction.

The length of the rotating bands on M107 projectiles is 1.02 - .04 in, and they have one cannelure 0.54 - .06 in. back from the leading edge. (The cross section of these bands is shown in Fig. 1.) During engraving, the band metal is forced backwards into the cannelure filling it to some extent so that the wall pressure in this region is not zero and cannot readily be calculated. Therefore, the maximum length of rotating band contact used in the calculation of coefficients of friction during the engraving process was 0.51 in. which obviated the uncertainities in the cannelure region. (Average values of rotating band and forcing cone dimensions were used in these calculations.) A further complication was the shallow circumferential grooves machined into the forcing cone of this particular gun tube. However, visual observation indicates that they are quickly filled with band metal and so they were not considered in the calculations.

The exact depth of ram of the projectile was very critical because the travel at which the Rforce was determined was the length of contact (0.51 in. maximum) less the depth of ram. It was not measured in the firing experiments but usually is somewhere between 3/16 and 1/4 in. Therefore, friction coefficients were calculated using both of these

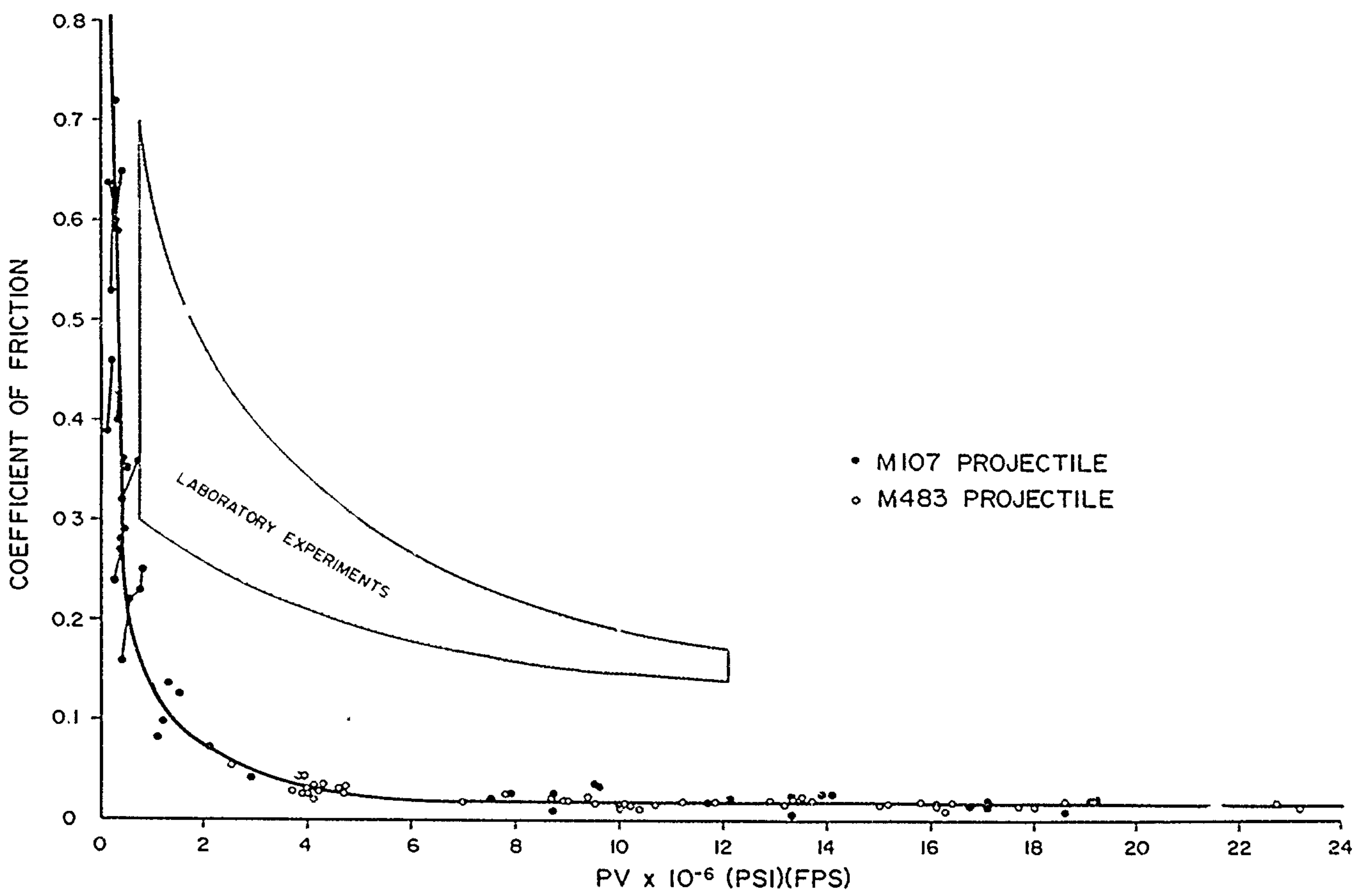


Fig. 2 Coefficient of friction as a function of the product of bearing pressure and sliding velocity.

ram depths for each band contact length. This produced two values with the actual friction coefficient somewhere between them. A total of three band contact lengths were used which resulted in three sets of double points for each round. These data are given in Table II.

Results

The coefficient of friction for gilding metal rotating bands is plotted as a function of the product of bearing pressure and velocity in Fig. 2. The initial friction was very high but it rapidly dropped to perhaps 0.1 by the time the bands were completely engraved. The location of the friction drop indicated that the formation of a molten surface film occurred at a considerably lower PV with these actual rotating bands than it had in the laboratory pin-on-disk experiments. This was no doubt owing to the additional sources of heat. (The band of laboratory coefficients of friction is drawn on Fig. 2 for comparison.) The equilibrium coefficient of friction, which appears to be about 0.02, is reached after about 5 in. of travel in this case. In Fig. 2, the coefficient of friction slowly falls with increased travel beyond this point but this probably was an artifact caused by neglecting the wear of the rotating bands.

Conclusion

The molten film is formed on the surface of gilding metal rotating bands at a bearing pressure-velocity value of approximately 0.8×10^6 (psi)(fps). This was reached well before the bands were completely engraved in the case of a 155mm howitzer firing at low zones. It would be reached even more rapidly in the case of tank guns or artillery firing at higher zones. Therefore, with the exception of engraving, the sliding of gilding metal banded projectiles down a gun tube must be considered hydrodynamic-lubricated sliding with the coefficient of friction determined only by the character of the film and not by the properties of the sliding surfaces themselves. Furthermore, the wear of these rotating bands would be dependent only on the amount of heat transferred to them.

References

(1) R. S. Montgomery, "Friction and Wear at High Sliding Speeds", Watervliet Arsenal Report 75028 (1975).

(2) W. F. Hartman and P. P. Stirbis, "Rotating Band Pressures and Engraving Forces in 155mm Gun Tubes as Deduced from Quasi-Static Push Tests", U.S. Army Report SC-RR-71 0457 (1971).

(3) J. O. Pilcher, U.S. Army Ballistics Research Laboratory, Private Communication (1975)

Acknowledgment

The firing data from the Feltman Research Laboratory at Picatinny Arsenal was obtained through the courtesy of Mr. George Demitrack.

TABLE I

155mm Howitzer M185 Firing Data (1.0 in. to 20.0 in.)

Round No.		316	318	319	320	330	331	313
Projectile		M107	M107	M107	M107	M107	M107	M483A1
Tube		2	2	2	2	4	4	2
Zone		1	1	2	2	1	1	2
1.0 in. Travel	Vel. (in/sec)	700	310	510	368	264	298	----
	Rforce $x10^{-3}$ (lbf)	40	132	70	121	79	95	----
	PV x 10^{-6} (psi) (fps)	2.9	1.3	2.1	1.5	1.1	1.2	----
	Coef. of Friction	.042	.138	.073	.126	.082	.099	----
2.0 in. Travel	Vel. (in/sec)	----	----	----	----	----	----	912
	Rforce $x10^{-3}$ (lbf)	----	----	----	----	----	----	62
	PV $x10^{-6}$ (psi) (fps)	----	----	----	----	----	----	3.8
	Coef. of Friction	----	----	----	----	----	----	.043
5.0 in. Travel	Vel. (in/sec)	2100	2080	2280	2300	1800	1900	2080
	Rforce $x10^{-3}$ (lbf)	26	10	35	33	20	25	32
	PV $x10^{-6}$ (psi) (fps)	8.7	8.7	9.5	9.6	7.5	7.9	8.7
	Coef. of Friction	.027	.010	.036	.034	.021	.026	.022
10.0 in. Travel	Vel. (in/sec)	3200	3200	3380	3340	2820	2900	3100
	Rforce $x10^{-3}$ (lbf)	22	5	26	25	17	20	26
	PV $x10^{-6}$ (psi) (fps)	13.3	13.3	14.1	13.9	11.7	12.1	12.9
	Coef. of Friction	.023	.005	.027	.026	.018	.021	.018
20.0 in. Travel	Vel. (in/sec)	4100	4460	4600	4600	4040	4100	4240
	Rforce $x10^{-3}$ (lbf)	19	8	20	20	14	16	20
	PV $x10^{-6}$ (psi) (fps)	17.1	18.6	19.2	19.2	16.8	17.1	17.7
	Coef. of Friction	.020	.008	.021	.021	.015	.017	.014

Tube 2 had previously fired approx. 150 rounds.
Tube 4 had previously fired 600-800 rounds.
The propellent was M3A1.
Both projectiles had gilding metal (90 Cu-10Zn) rotating bands.
The band bearing area was 19.2 in^2 for the M107 and 28.5 in^2 for the M483 A1 projectile.

TABLE I (Cont'd)

		314	315	324	337	338	339	340
Round No.		314	315	324	337	338	339	340
Projectile		M483A1	M483A1	M483A1	M483A1	M483A1	M483A1	M483A1
Tube		2	2	4	4	4	4	4
Zone		2	2	1	2	2	2	3
1.0 in. Travel	Vel. (in/sec)	----	----	----	----	----	----	----
	Rforce $x10^{-3}$(lbf)	----	----	----	----	----	----	----
	PV x 10^{-6}(psi)(fps)	----	----	----	----	----	----	----
	Coef. of Friction	----	----	----	----	----	----	----
2.0 in. Travel	Vel. (in/sec)	968	996	892	1096	1008	1120	968
	Rforce $x10^{-3}$(lbf)	46	30	43	45	41	38	38
	PV $x10^{-6}$ (psi)(fps)	4.0	4.1	3.7	4.6	4.2	4.7	4.0
	Coef. of Friction	.032	.021	.030	.032	.029	.027	.027
5.0 in. Travel	Vel. (in/sec)	2140	----	1900	2260	2160	2280	2460
	Rforce $x10^{-3}$(lbf)	28	----	36	32	28	27	23
	PV $x10^{-6}$(psi)(fps)	8.9	----	7.9	9.4	9.0	9.5	10.2
	Coef. of Friction	.020	----	.025	.022	.020	.019	.016
10.0 in. Travel	Vel. (in/sec)	3180	----	2840	3240	3200	3300	3600
	Rforce $x10^{-3}$(lbf)	22	----	27	32	28	27	23
	PV $x10^{-6}$(psi)(fps)	13.2	----	11.8	13.5	13.3	13.7	15.0
	Coef. of Friction	.015	----	.019	.022	.020	.019	.016
20.0 in. Travel	Vel. (in/sec)	4320	----	3940	4460	----	----	----
	Rforce $x10^{-3}$(lbf)	17	----	27	26	----	----	----
	PV $x10^{-6}$(psi)(fps)	18.0	----	16.4	18.6	----	----	----
	Coef. of Friction	.012	----	.019	.018	----	----	----

TABLE I (Cont'd)

		341	342	345	346	347	360
Round No.		341	342	345	346	347	360
Projectile		M483A1	M483A1	M483A1	M483A1	M483A1	M483A1
Tube		4	4	2	2	2	2
Zone		3	3	3	3	3	1
1.0 in. Travel	Vel. (in/sec)	----	----	----	----	----	----
	Rforce $x10^{-3}$ (lbf)	----	----	----	----	----	----
	PV x 10^{-6} (psi)(fps)	----	----	----	----	----	----
	Coef. of Friction	----	----	----	----	----	----
2.0 in. Travel	Vel. (in/sec)	936	932	980	1040	1120	600
	Rforce $x10^{-3}$ (lbf)	37	60	50	53	50	79
	PV $x10^{-6}$ (psi)(fps)	3.9	3.9	4.1	4.3	4.7	2.5
	Coef. of Friction	.026	.042	.035	.037	.035	.055
5.0 in. Travel	Vel. (in/sec)	2400	2400	2420	2500	2560	1680
	Rforce $x10^{-3}$ (lbf)	19	15	22	16	23	25
	PV $x10^{-6}$ (psi)(fps)	10.0	10.0	10.1	10.4	10.7	7.0
	Coef. of Friction	.013	.010	.015	.011	.016	.018
10.0 in. Travel	Vel. (in/sec)	3660	----	3860	3920	3860	2700
	Rforce $x10^{-3}$ (lbf)	21	----	22	13	23	25
	PV $x10^{-6}$ (psi)(fps)	15.2	----	16.1	16.3	16.1	11.2
	Coef. of Friction	.015	----	.015	.009	.016	.018
20.0 in. Travel	Vel. (in/sec)	----	----	----	5580	5440	3800
	Rforce $x10^{-3}$ (lbf)	----	----	----	16	23	25
	PV $x10^{-6}$ (psi)(fps)	----	----	----	23.2	22.7	15.8
	Coef. of Friction	----	----	----	.011	.016	.018

Table II

155mm M185 Howitzer Firing Data with M107 Projectiles and Tube No. 2
(.14 in. to .32 in.)

Round No.	316					
Length of contact	0.51 in.		0.45 in.		0.366 in.	
Ram (Travel)	3/16 (.32)in	1/4 (.26)in	3/16 (.26)in	1/4 (.20)in	3/16(.20)in	1/4(.14)in
Vel. (in/sec)	248	240	240	14[illegible]	144	7[illegible]
Rforce x 10^{-3}(lbf)	94	87	8[illegible]	8[illegible]	80	86
PV x 10^{-6}(psi)(fps)	0.81	0.78	[illegible].68	0.41	0.35	0.17
Coef. of Friction	0.25	0.23	0.36	0.52	0.59	0.64

Round No.	318					
Length of contact	0.51 in.		0.45 in.		0.366 in.	
Ram (Travel)	3/16(.32)in	1/4(.26)in	3/16(.26)in	1/4(.20)in	3/16(.20)in	1/4(.14)in
Vel. (in/sec)	164	120	120	86	86	34
Rforce x 10^{-3}(lbf)	86	70	70	65	65	57
PV x 10^{-6}(psi)(fps)	0.54	0.39	0.34	.24	.21	.08
Coef. of Friction	0.22	0.16	0.27	0.24	0.46	.39

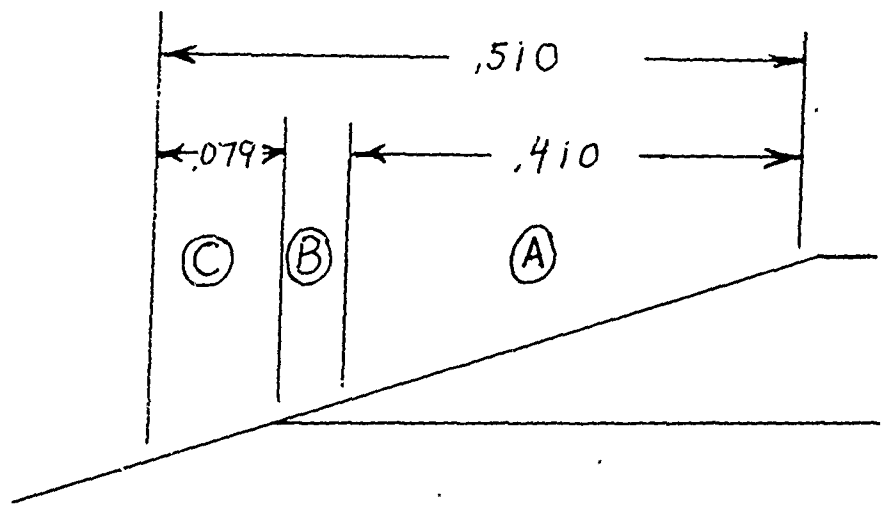
Round No.	319					
Length of contact	0.51 in.		0.45 in.		0.366 in.	
Ram (Travel)	3/16(.32)in	1/4(.26)in	3/16(.26)in	1/4(.20)in	3/16(.20)in	1/4(.14)in
Vel. (in/sec)	224	172	175	150	150	96
Rforce x 10^{-3}(lbf)	87	86	86	87	87	81
PV x 10^{-6}(psi)(fps)	.73	.56	.49	.42	.36	.23
Coef. of Friction	.23	.22	.55	.36	.65	.60

Round No.	320					
Length of contact	0.51 in.		0.45 in.		0.366 in.	
Ram (Travel)	3/16(.32)in	1/4(.26)in	3/16(.26)in	1/4(.20)in	3/16(.20)in	1/4(.14)in
Vel. (in/sec)	136	117	117	104	104	78
Rforce x 10^{-3}(lbf)	105	100	100	95	95	73
PV x 10^{-6}(psi)(fps)	.44	.38	.33	.29	.25	.19
Coef. of Friction	.29	.28	.43	.40	.72	.53

APPENDIX

CALCULATION OF COEFFICIENTS OF FRICTION DURING THE ENGRAVING PROCESS

0.51 in. Length of Contact



Region A (lands)

Height of lands at leading edge = $0.431 \tan\alpha$

$= (0.431)(0.1016) = 0.044$ in.

Bore diameter at leading edge $= 6.200 - 2(0.044) = 6.112$ in

Penetration at leading edge $= \dfrac{6.172 - 6.112}{2} = 0.030$ in.

Height of lands at trailing edge= $0.021 \tan\alpha$

$= (0.021)(0.1016) = 0.002$ in.

Bore diameter at trailing edge $= 6.200 - 2(0.002) = 6.196$ in.

Penetration at trailing edge $= \dfrac{6.216 - 6.196}{2} = 0.010$ in.

Penetration pressure (Fig. 3) $= 55 \times 10^3$ psi

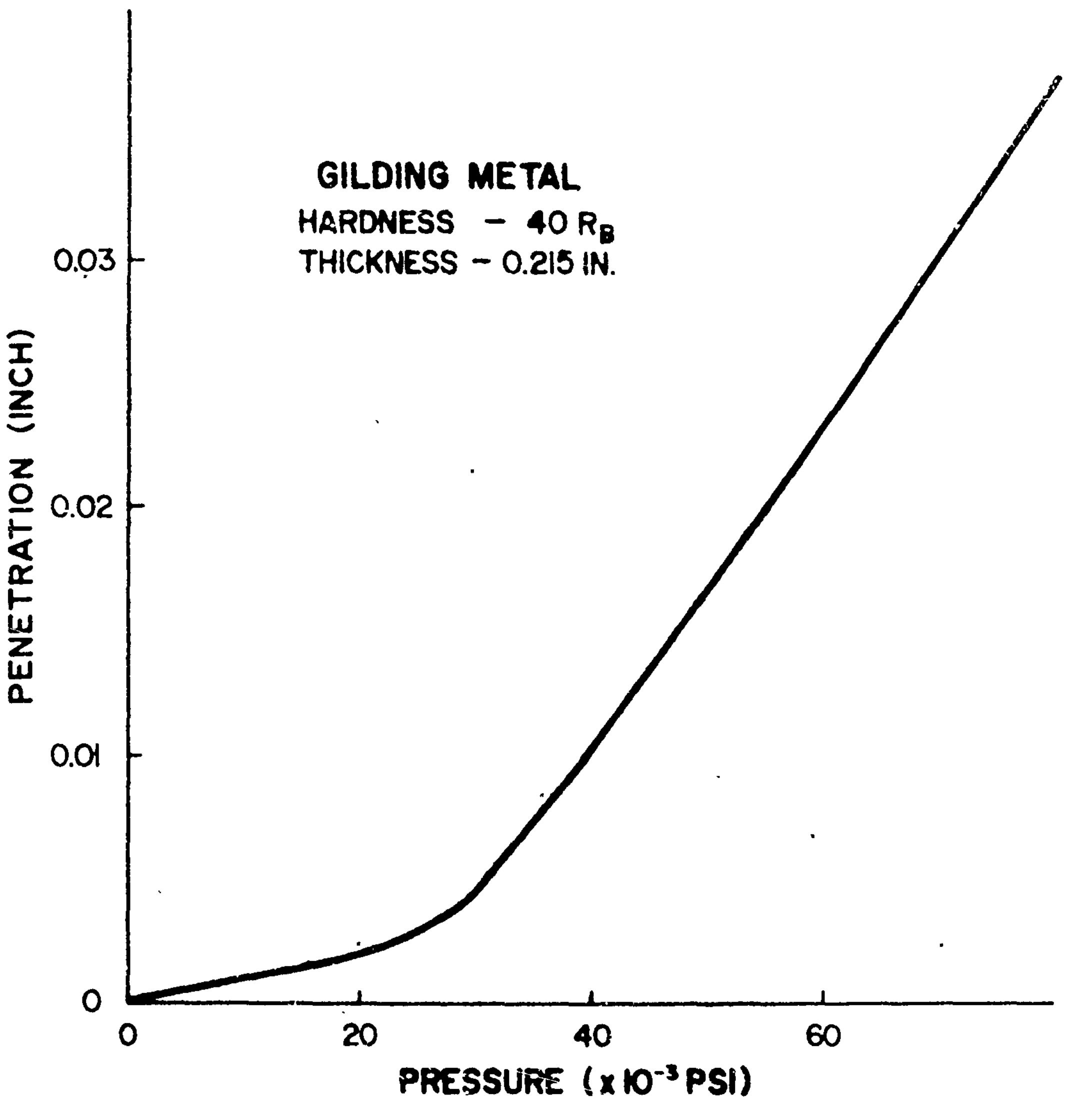


Fig. 3 Penetration as a function of pressure (derived from data in Ref. (2)).

Area = 0.410 (total width of lands)

= (0.410)(48)(0.15) = 2.95 in^2

Force on Wall = (2.95)(55 x 10^3) = 162 x 10^3 lbf

Rforce = 162 x 10^3 ($\sin\alpha + f \cos\alpha$)

Region A (grooves)

Penetration at trailing edge $= \frac{6.216 - 6.200}{2} = 0.008$ in.

Distance to leading edge contact (zero Penetration) $= \frac{0.008}{\tan 3°} = 0.153$ in.

Penetration pressure (Fig. 3) = 26 x 10^3 psi

Area = 0.079 (total width of grooves)

= (0.153)(6.20 π - (48)(0.15)) = 1.88 in^2

Force on wall = (1.88)(26 x 10^3) = 49 x 10^3 lbf

Rforce = 49 x 10^3 ($\sin\alpha + f\cos\alpha$)

Region B (lands)

Penetration at leading edge = 0.010 in.

Penetration at trailing edge= 0.008 in.

Penetration pressure (Fig. 3)=38 x 10^3 psi

Area = (0.021)(48)(0.15) = 0.15 in^2

Force on wall = (0.15)(38x 10^3) = 6 x 10^3 psi

Rforce = 6 x 10^3 ($\sin\alpha + f \cos\alpha$)

Region B (grooves)

Penetration - 0.008 in.

Penetration pressure (Fig. 3) = 35 x 10^3 psi

Area = (0.021)(6.20π -(48)(0.15)) = 0.26 in^2

Force on wall = (0.26) (35 x 10^3) = 9 x 10^3 lbf

Rforce = 9 x 10^3 ($\sin\alpha + f\cos\alpha$)

Region C

Penetration at leading edge=0.008 in.

Penetration at trailing edge = 0.000 in.

Penetration pressure (Fig. 3) = 26×10^3 psi.

Area = $0.079\ (6.20\pi) = 1.54\ in^2$

Force on wall = $(1.54)(26 \times 10^3) = 40 \times 10^3$ lbf

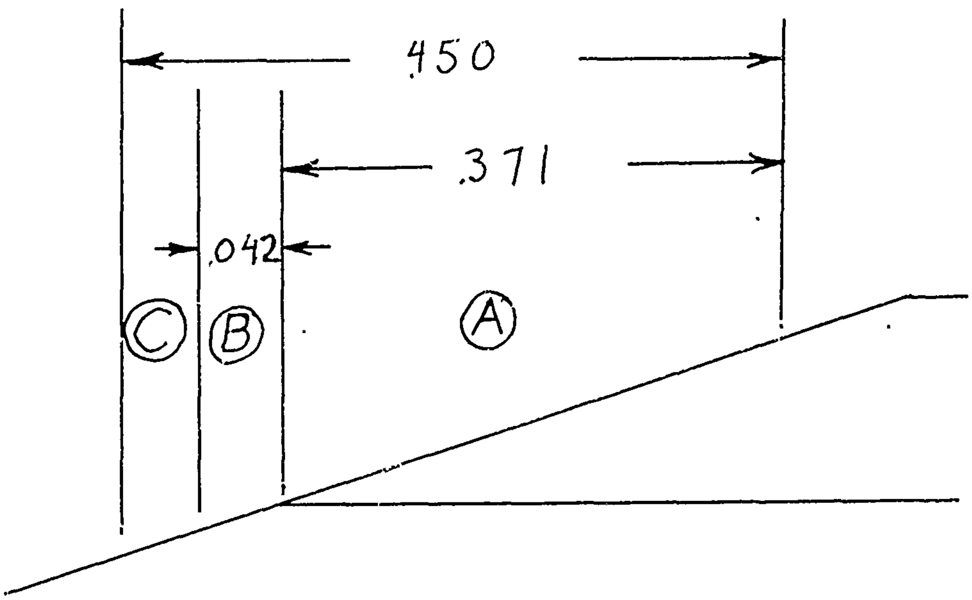
Rforce = $40 \times 10^3\ (\sin\alpha\ +\ f \cos\alpha\ )$

Total Rforce = $266 \times 10^3\ (\sin\ \ +\ f \cos\ \ )$

$= 265\ f + 27$

$$f = \frac{\text{Rforce} - 27 \times 10^3}{265 \times 10^3}$$

0.45 in Length of Contact



Region A (lands)

Height of lands at leading edge = (0.371)(.1016) = 0.038 in.

Penetration at leading edge = $\frac{6.172 - 6.124}{2}$ = 0.024 in.

Diameter of band at trailing edge = 6.216 - 2(.042) tan 3°

= 6.212 in.

Penetration at trailing edge = $\frac{6.212 - 6.200}{2}$

= 0.006 in.

Penetration pressure (Fig. 3) = 47 x 10^3 psi

Area = (0.371)(48)(0.15) = 2.67 in^2

Force on wall = (2.67)(47 x 10^3) = 125 x 10^3 16f

Rforce = 125 x 10^3 ($\sin\alpha + f \cos\alpha$)

Region A (grooves)

Penetration at trailing edge = 0.006 in.

Distance from trailing edge to zero contact = $\frac{0.006}{\tan 3°}$ = 0.114 in.

Penetration pressure (Fig. 3) = 19 x 10^3 psi

Area = (0.114)(12.27) = 1.40 in^2

Force on wall = (1.40)(19 x 10^3) = 27 x 10^3 lbf

Rforce = 27 x 10^3 ($\sin\alpha + f \cos\alpha$)

Region B

Penetration at leading edge = 0.006 in.

Bore diameter at trailing edge =6.200 + (0.042)(0.20315)

=6.208 in.

Penetration at trailing edge =$\frac{6.216 - 6.208}{2}$

=0.004 in.

Penetration pressure (Fig. 3) = 31×10^3 psi

Area = $(0.042)(6.200\pi) = 0.82$ in^2

Force on wall = $(0.82)(31 \times 10^3)$

$= 25 \times 10^3$ lbf

Rforce = $25 \times 10^3 (\sin\alpha + f \cos\alpha)$

Region C

Penetration at leading edge = 0.004 in.

Penetration at trailing edge= 0.000 in.

Penetration pressure (Fig. 3) = 18×10^3 psi

Area = $(0.037)(6.200\pi)$ 0.72 in^2

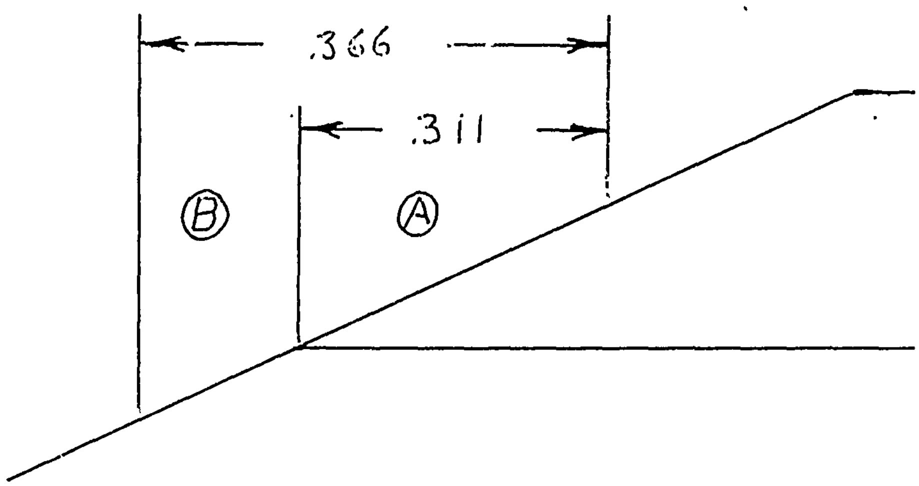
Force on wall = 13×10^3 lbf

Rforce = $13 \times 10^3 (\sin\alpha + f \cos\alpha)$

Total Rforce = $190 \times 10^3 (\sin\alpha + f \cos\alpha)$

$$f = \frac{\text{Rforce} - 19 \times 10^3}{189 \times 10^3}$$

0.366 Length of Contact



Region A (lands)

Height of lands at leading edge = (0.311)(0.1016)

= 0.032 in.

Penetration at leading edge $= \dfrac{6.172 - 6.136}{2}$

= 0.018 in.

Height of lands at trailing edge= 0.000 in.

Diameter of band at trailing edge=6.216 -(.099)(2 tan 3°)

=6.206 in.

Penetration at trailing edge $= \dfrac{6.206 - 6.200}{2}$

=0.003 in.

Penetration pressure (Fig. 3) $= 40 \times 10^3$ psi

Area = (0.311)(48)(0.15) = 2.24 in.^{2}

Force on wall = $(2.24)(40 \times 10^3)$

$= 90 \times 10^3$ lbf

Rforce = $90 \times 10^3 (\sin\alpha + f \cos\alpha)$

Region A (grooves)

Penetration at trailing edge = 0.003 in.

Penetration at leading edge = 0.000 in.

Penetration pressure (Fig. 3) = 15×10^3 psi

Distance from trailing edge to zero contact $= \dfrac{0.003}{\tan 3^\circ}$

= 0.057 in.

Area = (12.27)(0.057) = 0.70 in^2

Force on wall = $(0.70)(15 \times 10^3) = 10 \times 10^3$ lbf

Rforce = $10 \times 10^3 (\sin\alpha + f \cos\alpha)$

Region B

Penetration at leading edge $= 0.003$ in.

Penetration at trailing edge $= 0.000$ in.

Penetration Pressure (Fig. 3) $= 15 \times 10^3$ psi

Calculation of length of contact ———

Diameter of band at zero penetration = Diameter of chamber at zero penetration

$$6.216 - 2 \tan 3° \,(0.41 - \text{length of contact}) = 6.200 + 0.20315\,(\text{length of contact} - 0.311)$$

$$6.173 + 0.1048\,(\text{length of contact}) = 6.137 + 0.20315\,(\text{length of contact})$$

$$\text{Length of contact} = \frac{0.036}{0.09833} = 0.366 \text{ in.}$$

$$\text{Length of Region B} = 0.366 - 0.311 = 0.055 \text{ in.}$$

$$\text{Area} = (0.055)(6.20\,\pi) = 1.07 \text{ in}^2$$

$$\text{Force on wall} = (1.07)(15 \times 10^3) = 16 \times 10^3 \text{ lbf}$$

$$\text{Rforce} = 16 \times 10^3 \,(\sin\alpha + f \cos\alpha)$$

$$\text{Total Rforce} = 116 \times 10^3 \,(\sin\alpha + f \cos\alpha)$$

$$f = \frac{\text{Rforce} - 12 \times 10^3}{115 \times 10^3}$$
